Anisotropic pure-phase plates for quality improvement of partially coherent, partially polarized beams

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Received July 17, 2002; revised manuscript received October 24, 2002; accepted October 30, 2002

From a theoretical point of view, the use of anisotropic pure-phase plates (APP) is considered in order to improve the quality parameter of certain partially coherent, partially polarized beams. It is shown that, to optimize the beam-quality parameter, the phases of the two Cartesian components of the field at the output of the APP plate should be identical and should exhibit a quadratic dependence on the radial polar coordinate.

OCIS codes: 260.0260, 260.5430, 160.1190.

1. INTRODUCTION

The global characterization of the spatial structure of laser fields by means of the intensity moments of the beam profile is a topic of interest in the past ten years (see, for example, Refs. 1–11). Within this framework, the so-called beam-quality parameter has received special attention in the literature: In fact, the propagation features through optical systems as well as a number of optimization criteria have been investigated in detail.[12,13] In particular, phase plates have been shown to be useful to improve the beam quality, since the output total intensity is maintained and the hard-edge diffraction effects are not significant. Previous papers have mainly been devoted to the scalar case, without taking the vectorial nature of light into account. This is equivalent to assuming uniformly totally polarized beams and nonaltering polarization devices. However, it is recognized that beams are, in general, partially polarized and can exhibit a nonuniform distribution of the polarization state across their transversal section. In this connection, the intensity moment formalism has been extended in past years[14–19] to include such vectorial behavior. Thus a generalized quality parameter has been reported,[20] which can be improved by means of certain optical arrangements[21,22] (e.g., Mach–Zehnder interferometric devices or lenslike birefringent elements, to mention only two).

In this paper, attention is focused on the use of anisotropic pure-phase (APP) plates to improve the beam-quality parameter of an important class of partially coherent, partially polarized beams. More specifically, given a beam, we analytically determine the phase transmittance function of the APP plate that the beam should travel along to attain the best quality without reducing the total power.

2. KEY DEFINITIONS

Let us consider partially coherent, partially polarized beams whose beam coherence-polarization (BCP) matrix[16,17] $\hat{\Gamma}$ contains diagonal elements of the form

$$\Gamma_{jj}(\mathbf{r}_1,\mathbf{r}_2) = \overline{E_j^*(\mathbf{r}_1)E_j(\mathbf{r}_2)} = A_j(\mathbf{r}_1,\mathbf{r}_2)\exp\{i[\alpha_j(\mathbf{r}_2)-\alpha_j(\mathbf{r}_1)]\}, \quad j=s,p \tag{1}$$

where s and p refer to the components of the electric field $\mathbf{E}$ orthogonal to the propagation direction z of the beam, the overbar denotes an ensemble average, $\mathbf{r}_1$ and $\mathbf{r}_2$ are position vectors at a plane transversal to the z axis, and the real function A fulfills

$$A_s(\mathbf{r}_1,\mathbf{r}_2) = A_s(\mathbf{r}_2,\mathbf{r}_1), \tag{2.1}$$

$$A_p(\mathbf{r}_1,\mathbf{r}_2) = A_p(\mathbf{r}_2,\mathbf{r}_1), \tag{2.2}$$

$$A_s(\mathbf{r},\mathbf{r}) \geqslant 0, \qquad A_p(\mathbf{r},\mathbf{r}) \geqslant 0. \tag{2.3}$$

To write Eq. (1), we assume the longitudinal component (along z) of the electric field vector $\mathbf{E}$ to be negligible,[23] within the framework of the paraxial approach. The total intensities associated with the field components s and p are then given by

$$I_j = \iint \Gamma_{jj}(\mathbf{r},\mathbf{r})\mathrm{d}\mathbf{r}, \qquad j=s,p. \tag{3}$$

For simplicity, we will choose our reference system in such a way that $I_s = I_p$. It should be pointed out that the type of fields we handle in the present paper include those beams whose amplitude at any plane z (including the waist plane) can be written as an incoherent superposition of Hermite–Gauss modes. In particular, the so-called partially polarized Gaussian Schell-model sources are important examples of this class of fields.[19,24]

Let us now consider a thin APP plate. This optical element can be represented, in the same reference system as before, by the following Jones matrix[25]:

$$T(\mathbf{r}) = \begin{bmatrix} \exp[i\Delta_s(\mathbf{r})] & 0 \\ 0 & \exp[i\Delta_p(\mathbf{r})] \end{bmatrix}. \tag{4}$$

The beam at the output of the APP plate is then characterized by a BCP matrix whose diagonal elements are

$$\Gamma_{ss}^{o}(\mathbf{r}_1, \mathbf{r}_2) = A_s(\mathbf{r}_1, \mathbf{r}_2)\exp\{i[\varphi_s(\mathbf{r}_2) - \varphi_s(\mathbf{r}_1)]\}, \quad (5)$$

$$\Gamma_{pp}^{o}(\mathbf{r}_1, \mathbf{r}_2) = A_p(\mathbf{r}_1, \mathbf{r}_2)\exp\{i[\varphi_p(\mathbf{r}_2) - \varphi_p(\mathbf{r}_1)]\}, \quad (6)$$

where the subscript o refers to the output plane of the APP plate and

$$\varphi_s(\mathbf{r}) = \alpha_s(\mathbf{r}) + \Delta_s(\mathbf{r}), \quad (7)$$

$$\varphi_p(\mathbf{r}) = \alpha_p(\mathbf{r}) + \Delta_p(\mathbf{r}). \quad (8)$$

Note that the intensities are preserved under propagation through this kind of systems.

As was pointed out in Section 1, here we are concerned with the so-called beam-quality parameter. For partially coherent and partially polarized beams, this parameter is defined in the form[20]

$$Q = \langle r^2\rangle\langle \eta^2\rangle - \langle \mathbf{r}\cdot\boldsymbol{\eta}\rangle^2, \quad (9)$$

where $\boldsymbol{\eta} = (u, v)$ is a vector whose components represent angles of propagation (without taking the evanescent waves into account) and the angle brackets denote the second-order intensity moments of the global beam, which now include both components, namely,

$$\langle r^2\rangle = \frac{I_s}{I}\langle r^2\rangle_s + \frac{I_p}{I}\langle r^2\rangle_p, \quad (10)$$

$$\langle \eta^2\rangle = \frac{I_s}{I}\langle \eta^2\rangle_s + \frac{I_p}{I}\langle \eta^2\rangle_p, \quad (11)$$

$$\langle \mathbf{r}\cdot\boldsymbol{\eta}\rangle = \frac{I_s}{I}\langle \mathbf{r}\cdot\eta\rangle_s + \frac{I_p}{I}\langle \mathbf{r}\cdot\boldsymbol{\eta}\rangle_p, \quad (12)$$

with $I = I_s + I_p = 2I_s = 2I_p$ (since $I_s = I_p$ in our coordinate reference system).

In these equations,

$$\langle\alpha\beta\rangle_j = \frac{1}{I_j}\frac{k^2}{4\pi^2} \times \iint \overline{\alpha\beta E_j^*(\mathbf{r} + \mathbf{s}/2, z)E_j(\mathbf{r} - \mathbf{s}/2, z)} \times \exp(ik\mathbf{s}\cdot\boldsymbol{\eta})\mathrm{d}\mathbf{r}\mathrm{d}\boldsymbol{\eta}\mathrm{d}\mathbf{s},$$

$$j = s, p, \quad \alpha,\beta = x, y, u, v, \quad (13)$$

where k denotes the wave number of the light beam. Without loss of generality, it has been assumed for simplicity that $\langle r\rangle = \langle \eta\rangle = 0$ (this is equivalent to a shift of the coordinate system). As usual, $\langle r^2\rangle$, $\langle \eta^2\rangle$, and $\langle \mathbf{r}\cdot\boldsymbol{\eta}\rangle$ are closely connected to the beam size, the beam divergence, and the average of the radius of curvature of the global beam. The interpretation of Q as a quality parameter relies, on the one hand, on its invariance under free propagation (consequently, Q represents an intrinsic characteristic of each beam) and, on the other hand, on the joint information about certain meaningful space and spatial-frequency beam features, namely, the minimum beam width and the far-field divergence. It thus contains information about the simultaneous focusing and collimation capabilities of the light field. It is also important to note that, for any beam, Q satisfies the inequality $Q \geqslant 1/k^2$, where the equality holds for uniformly totally polarized Gaussian beams.

3. IMPROVEMENT OF THE BEAM-QUALITY PARAMETER

From Eqs. (5), (6), and (10)–(12), it follows (see Appendix A) that the quality parameter of the beam at the output of an APP plate can be written as

$$Q^o = \langle r^2\rangle G + F, \quad (14)$$

where $\langle r^2\rangle$ refers to the input plane, the parameter

$$G = \frac{1}{k^2 I}\left[\iint \left(\frac{\partial^2 A_s}{\partial x_1\partial x_2} + \frac{\partial^2 A_s}{\partial y_1\partial y_2}\right)_{x_1=x_2=x;y_1=y_2=y}\mathrm{d}x\mathrm{d}y + \iint \left(\frac{\partial^2 A_p}{\partial x_1\partial x_2} + \frac{\partial^2 A_p}{\partial y_1\partial y_2}\right)_{x_1=x_2=x;y_1=y_2=y}\mathrm{d}x\mathrm{d}y\right] \quad (15)$$

depends only on the intensity characteristics of the input beam (consequently, it does not change upon propagation through the APP plate), and the term

$$F = \frac{\langle r^2\rangle}{k^2 I}\left[\iint |\nabla\varphi_s|^2 A_s(\mathbf{r}, \mathbf{r})\mathrm{d}x\mathrm{d}y + \iint |\nabla\varphi_p|^2 A_p(\mathbf{r}, \mathbf{r})\mathrm{d}x\mathrm{d}y\right] - \left[\frac{1}{kI}\iint (\mathbf{r}\cdot\nabla\varphi_s)A_s(\mathbf{r}, \mathbf{r})\mathrm{d}x\mathrm{d}y + \frac{1}{kI}\iint (\mathbf{r}\cdot\nabla\varphi_p)A_p(\mathbf{r}, \mathbf{r})\mathrm{d}x\mathrm{d}y\right]^2 \quad (16)$$

carries the information of both the phase of the input beam and the phase delay between the s and p components introduced by the APP plate.

We see that the value of the quality parameter depends on the sign of F. Since F is always positive (see Appendix B), it is clear that the best quality will be attained when $F = 0$. It can be shown (see Appendix B) that this occurs when

$$\Delta_s(\mathbf{r}) + \alpha_s(\mathbf{r}) = \Delta_p(\mathbf{r}) + \alpha_p(\mathbf{r}) = \mu r^2, \quad (17)$$

where μ is a real-valued constant.

Accordingly, from Eq. (17), we find that, for the beams we consider here, the quality parameter would become optimized, provided that

1. The phases of the two field components at the output of the APP plate are identical,
2. The phase of the beam at the output plane of the APP plate exhibits a quadratic dependence on the radial coordinate r.

Since the quadratic phase factor μr^2 corresponds to the insertion of a lens (which does not change the beam-quality parameter), essentially, Eq. (17) prescribes that, to optimize the quality, the best we can do is to remove the phase terms represented by the functions α_j, j

$= s, p$. It is interesting to note the consistency of this conclusion with regard to previous results derived in the scalar case.[13]

The physical meaning of Eq. (17) can also be illustrated by means of the following quite simple example: Let us consider a pure uniformly totally polarized Gaussian beam propagating through a ground glass. The BCP matrix of the output field would belong to the class of beams analyzed in this paper. It is clear that the quality parameter of the beam will be drastically affected by the action of the glass. To restore the original beam-quality value, it would obviously suffice to insert a plate that is phase conjugated with regard to the ground glass. But this is just what Eq. (17) recommends (disregarding any additional lens).

In a general case, when the phase terms α_j, $j = s, p$, are completely removed, the APP plate should then behave as a phase-conjugated filter matched to the phase transmittance of the light field. Equation (17) would then assure us that the quality parameter of the field emerging from such a phase conjugator (which can be realized in different ways)[26] will attain the minimum value (highest quality) one can reach by using pure-phase transmittances.

APPENDIX A

Here we will demonstrate Eq. (14).

Since we handle pure-phase plates, it is easy to see that

$$\langle r^2\rangle^o = \langle r^2\rangle^i, \tag{A1}$$

where the superscripts i and o refer to the input and the output planes of the APP plate.

We next calculate the output beam divergence [see Eq. (11)]:

$$\langle \eta^2\rangle^o = \frac{I_s}{I}\langle \eta^2\rangle_s^o + \frac{I_p}{I}\langle \eta^2\rangle_p^o. \tag{A2}$$

Let us first consider the s component. In terms of the elements Γ_{ss} of the BCP matrix, the moment $\langle \eta^2\rangle_s^o$ follows an expression similar to the scalar case (see, for example, Refs. 3 and 7), and it reads

$$\begin{aligned}\langle \eta^2\rangle_s^o = \frac{-1}{2k^2 I}\Bigg\{ &\iint \left[\frac{\partial^2\Gamma_{ss}^o(\mathbf{r}_1,\mathbf{r}_2)}{\partial x_1^2} + \frac{\partial^2\Gamma_{ss}^o(\mathbf{r}_1,\mathbf{r}_2)}{\partial x_2^2}\right.\\ &\left.- 2\frac{\partial^2\Gamma_{ss}^o(\mathbf{r}_1,\mathbf{r}_2)}{\partial x_1\partial x_2}\right]_{\mathbf{r}_1=\mathbf{r}_2=\mathbf{r}=(x,y)} \mathrm{d}x\mathrm{d}y\\ &+ \iint \left[\frac{\partial^2\Gamma_{ss}^o(\mathbf{r}_1,\mathbf{r}_2)}{\partial y_1^2} + \frac{\partial^2\Gamma_{ss}^o(\mathbf{r}_1,\mathbf{r}_2)}{\partial y_2^2}\right.\\ &\left.- 2\frac{\partial^2\Gamma_{ss}^o(\mathbf{r}_1,\mathbf{r}_2)}{\partial y_1\partial y_2}\right]_{\mathbf{r}=\mathbf{r}_2=\mathbf{r}=(x,y)} \mathrm{d}x\mathrm{d}y\Bigg\},\end{aligned} \tag{A3}$$

where $I = 2I_s = 2I_p$ in our coordinate reference system.

After application of Eq. (5), we find

$$\begin{aligned}\langle \eta^2\rangle_s^o = \frac{-1}{2k^2 I}\Bigg\{ &\iint \left[\frac{\partial^2 A_s(\mathbf{r}_1,\mathbf{r}_2)}{\partial x_1^2} + \frac{\partial^2 A_s(\mathbf{r}_1,\mathbf{r}_2)}{\partial x_2^2}\right.\\ &\left.- 2\frac{\partial^2 A_s(\mathbf{r}_1,\mathbf{r}_2)}{\partial x_1\partial x_2}\right]_{\mathbf{r}_1=\mathbf{r}_2=\mathbf{r}=(x,y)} \mathrm{d}x\mathrm{d}y\\ &+ \iint \left[\frac{\partial^2 A_s(\mathbf{r}_1,\mathbf{r}_2)}{\partial y_1^2} + \frac{\partial^2 A_s(\mathbf{r}_1,\mathbf{r}_2)}{\partial y_2^2}\right.\\ &\left.- 2\frac{\partial^2 A_s(\mathbf{r}_1,\mathbf{r}_2)}{\partial y_1\partial y_2}\right]_{\mathbf{r}_1=\mathbf{r}_2=\mathbf{r}=(x,y)} \mathrm{d}x\mathrm{d}y\Bigg\}\\ &+ \frac{1}{2k^2 I}\Bigg(\iint \left\{\left[\frac{\partial\varphi_s(\mathbf{r}_1)}{\partial x_1}\right]^2 + \left[\frac{\partial\varphi_s(\mathbf{r}_2)}{\partial x_2}\right]^2\right.\\ &\left.+ 2\left[\frac{\partial\varphi_s(\mathbf{r}_1)}{\partial x_1}\right]\left[\frac{\partial\varphi_s(\mathbf{r}_2)}{\partial x_2}\right]\right\}_{\mathbf{r}_1=\mathbf{r}_2=\mathbf{r}=(x,y)} A_s(\mathbf{r},\mathbf{r})\mathrm{d}x\mathrm{d}y\\ &+ \iint \left\{\left[\frac{\partial\varphi_s(\mathbf{r}_1)}{\partial y_1}\right]^2 + \left[\frac{\partial\varphi_s(\mathbf{r}_2)}{\partial y_2}\right]^2 + 2\left[\frac{\partial\varphi_s(\mathbf{r}_1)}{\partial y_1}\right]\right.\\ &\left.\times\left[\frac{\partial\varphi_s(\mathbf{r}_2)}{\partial y_2}\right]\right\}_{\mathbf{r}_1=\mathbf{r}_2=\mathbf{r}=(x,y)} A_s(\mathbf{r},\mathbf{r})\mathrm{d}x\mathrm{d}y\Bigg),\end{aligned} \tag{A4}$$

where Eq. (2.1) has been used. After some calculations we finally find

$$\begin{aligned}\langle \eta^2\rangle_s^o = \frac{2}{k^2 I}\iint &\left[\frac{\partial^2 A_s(\mathbf{r}_1,\mathbf{r}_2)}{\partial x_1\partial x_2}\right.\\ &\left.+ \frac{\partial^2 A_s(\mathbf{r}_1,\mathbf{r}_2)}{\partial y_1\partial y_2}\right]_{\mathbf{r}_1=\mathbf{r}_2=\mathbf{r}=(x,y)} \mathrm{d}x\mathrm{d}y\\ &+ \frac{2}{k^2 I}\iint |\nabla\varphi_s(\mathbf{r})|^2 A_s(\mathbf{r},\ \mathbf{r})\mathrm{d}x\mathrm{d}y,\end{aligned} \tag{A5}$$

so that [cf. Eq. (A2)]

$$\begin{aligned}\langle \eta^2\rangle^o = \frac{1}{k^2 I}\iint &\left[\frac{\partial^2(A_s + A_p)}{\partial x_1\partial x_2}\right.\\ &\left.+ \frac{\partial^2(A_s + A_p)}{\partial y_1\partial y_2}\right]_{\mathbf{r}_1=\mathbf{r}_2=\mathbf{r}=(x,y)} \mathrm{d}x\mathrm{d}y\\ &+ \frac{1}{k^2 I}\iint |\nabla\varphi_s(\mathbf{r})|^2 A_s(\mathbf{r},\ \mathbf{r})\\ &+ |\nabla\varphi_p(\mathbf{r})|^2 A_p(\mathbf{r},\ \mathbf{r})\mathrm{d}x\mathrm{d}y.\end{aligned} \tag{A6}$$

It remains for us to calculate the parameter $\langle \mathbf{r}\cdot\boldsymbol{\eta}\rangle$ [given by Eq. (12)] at the output of the APP plate. Taking into account the prescribed formula in the scalar case, we can now write

$$\langle \mathbf{r} \cdot \boldsymbol{\eta} \rangle_s^o = \frac{-1}{ikI} \left\{ \iint x \left[\frac{\partial \Gamma_{ss}^o(\mathbf{r}_1, \mathbf{r}_2)}{\partial x_1} - \frac{\partial \Gamma_{ss}^o(\mathbf{r}_1, \mathbf{r}_2)}{\partial x_2} \right]_{\mathbf{r}_1=\mathbf{r}_2=\mathbf{r}=(x,y)} \mathrm{d}x\mathrm{d}y - \iint y \left[\frac{\partial \Gamma_{ss}^o(\mathbf{r}_1, \mathbf{r}_2)}{\partial y_1} - \frac{\partial \Gamma_{ss}^o(\mathbf{r}_1, \mathbf{r}_2)}{\partial y_2} \right]_{\mathbf{r}_1=\mathbf{r}_2=\mathbf{r}=(x,y)} \mathrm{d}x\mathrm{d}y \right\}. \quad \text{(A7)}$$

After some algebra we get

$$\langle \mathbf{r} \cdot \boldsymbol{\eta} \rangle_s^o = \frac{2}{kI} \iint [\mathbf{r} \cdot |\nabla \varphi_s(\mathbf{r})|] \; A_s(\mathbf{r}, \mathbf{r}) \mathrm{d}x\mathrm{d}y, \quad \text{(A8)}$$

and, consequently,

$$\langle \mathbf{r} \cdot \boldsymbol{\eta} \rangle^o = \frac{1}{kI} \iint \{[\mathbf{r} \cdot |\nabla \varphi_s(\mathbf{r})|] A_s(\mathbf{r}, \mathbf{r}) + [\mathbf{r} \cdot |\nabla \varphi_p(\mathbf{r})|] A_p(\mathbf{r}, \mathbf{r})\} \mathrm{d}x\mathrm{d}y. \quad \text{(A9)}$$

Equation (14) finally follows from the direct application of Eqs. (A1), (A6), and (A9) to the definition of parameter Q [Eq. (9)].

APPENDIX B

We next show that $F \geqslant 0$.

Let us first define

$$m_j = \frac{1}{k^2 I} \iint |\nabla \varphi_j|^2 A_j(\mathbf{r}, \mathbf{r}) \mathrm{d}x\mathrm{d}y, \qquad j = s, p, \quad \text{(B1)}$$

$$M = \left(\frac{1}{kI} \iint \mathbf{r} \cdot \nabla \varphi_s \, A_s \mathrm{d}x\mathrm{d}y + \frac{1}{kI} \iint \mathbf{r} \cdot \nabla \varphi_p A_p \mathrm{d}x\mathrm{d}y \right)^2. \quad \text{(B2)}$$

We then have

$$M \leqslant \left(\frac{1}{kI} \left| \iint \mathbf{r} \cdot \nabla \varphi_s A_s \mathrm{d}x\mathrm{d}y \right| + \frac{1}{kI} \left| \iint \mathbf{r} \cdot \nabla \varphi_p A_p \mathrm{d}x\mathrm{d}y \right| \right)^2, \quad \text{(B3)}$$

where the equality is obtained when

$$\mathrm{sign}\left(\iint \mathbf{r} \cdot \nabla \varphi_s A_s \mathrm{d}x\mathrm{d}y \right) = \mathrm{sign}\left(\iint \mathbf{r} \cdot \nabla \varphi_p A_p \mathrm{d}x\mathrm{d}y \right). \quad \text{(B4)}$$

In addition, application of the Cauchy–Schwarz inequality gives

$$M \leqslant (\sqrt{\langle r^2 \rangle_s m_s} + \sqrt{\langle r^2 \rangle_p m_p})^2, \quad \text{(B5)}$$

and the equality follows when

$$\nabla \varphi_s = \rho \mathbf{r}, \qquad \nabla \varphi_p = \mu \mathbf{r}, \quad \text{(B6)}$$

where ρ and μ are constants. In terms of m_j and M, the function F can be expressed in the form

$$F = \langle r^2 \rangle (m_s + m_p) - M, \quad \text{(B7)}$$

and we finally get

$$F \geqslant (\langle r^2 \rangle_s + \langle r^2 \rangle_p)(m_s + m_p) - \langle r^2 \rangle_s m_s - \langle r^2 \rangle_p m_p - 2\sqrt{\langle r^2 \rangle_s \langle r^2 \rangle_p m_s m_p} = (\sqrt{\langle r^2 \rangle_p m_s} - \sqrt{\langle r^2 \rangle_s m_p})^2 \geqslant 0, \text{ Q.E.D.} \quad \text{(B8)}$$

In particular, $F = 0$ means that

$$\langle r^2 \rangle_p m_s = \langle r^2 \rangle_s m_p. \quad \text{(B9)}$$

It can then be shown that the above equality is fulfilled, provided that Eqs. (B4) and (B6) are satisfied for the same value of the constants ρ and μ.

ACKNOWLEDGMENTS

The research leading to this paper was supported by the Ministerio de Ciencia y Tecnología of Spain, project BFM2001-1356, within the framework of EUREKA project EU-2359. The authors also thank two anonymous referees for their suggestions that improved the content of this paper.

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